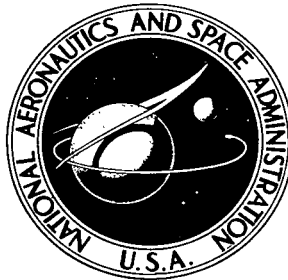


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# **GAS-JET IMPINGEMENT NORMAL TO A LIQUID SURFACE**

*by Thomas L. Labus and John C. Aydelott*

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Cleveland, Ohio 44135*



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# GAS-JET IMPINGEMENT NORMAL TO A LIQUID SURFACE

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## SUMMARY

An experimental and analytical investigation was conducted to determine the characteristics of a gaseous jet impinging normally on a liquid surface in regions where both gravitational and surface tension forces are significant. The surface penetration depths in the liquid resulting from a gas jet which exited from a circular aperture with an initially parabolic velocity profile were correlated in terms of a modified Weber number and a modified Bond number at ratios of the nozzle - liquid-surface distance to nozzle diameter ranging from 3 to 15. An expression was obtained for the limiting case of large modified Bond number, which is applicable to an environment where the gravitational force is dominant.

## INTRODUCTION

The NASA Lewis Research Center has been conducting basic and applied research to examine the static and dynamic behavior of liquids under reduced gravitational conditions. As a part of this research program, the problems associated with the dynamic effects of a gas jet impinging on a liquid surface are of interest. As Blackmon (ref. 1) points out, a knowledge of the effects on the liquid surface during propellant tank resurization in low gravity is extremely vital, since serious problems can result which will affect engine restarting, ullage venting, propellant transfer, and propellant orientation.

The first author (ref. 2) has studied the impingement of gaseous nitrogen on a distilled-water surface in weightlessness, where the sole restoring force affecting the resulting gas cavity is surface tension. In that reference, the penetration depth into the liquid was correlated in terms of the gas-jet momentum and the liquid surface tension.

Numerous authors (refs. 3 to 6) have examined the impingement phenomena in a gravity-dominated environment. Banks and Chandrasekhara (ref. 7) realized that even under normal-gravity conditions surface-tension forces would affect the resulting

penetration depth to some extent. In reference 7, an attempt was made to incorporate the effect of surface-tension forces by assuming that the cavity shape could be described by a normal error curve, which would allow a calculation of the radius of curvature at the stagnation point. However, all the data contained in reference 7 were for gas jets possessing an initially flat velocity profile and, therefore, cannot be employed for any other velocity profiles.

Rosler and Stewart (ref. 8) also attempted to incorporate the effects of surface tension. However, their experimental data, which employed initially parabolic gas jets in normal gravity, did not yield any measured penetration depths, since the main objectives in the study were to establish the regimes of stable, oscillating, and dispersing indentations as functions of the gas-jet velocity and surface tension. Also, the data were all taken with the issuing jet positioned above the liquid surface at a distance of 6.4 nozzle diameters.

In reference 9, the stability of the gas cavity in a weightless environment was examined. Finally, Blackmon (ref. 1), while indicating the governing equations for including the effects of both gravitational and surface-tension forces for the prediction of the cavity depth, concentrated solely on the effects of gravity for his particular application.

This report presents the results of an experimental and analytical investigation which is an extension of the original work conducted by the first author (ref. 2) to regions where both gravity and surface-tension forces are significant in determining the penetration depth.

## SYMBOLS

A	cross-sectional area of nozzle, cm
a	acceleration due to gravity, cm/sec <sup>2</sup>
Bo <sub>M</sub>	modified Bond number, $\rho_l a d^2 / \sigma$
d	nozzle diameter, cm
Fr <sub>M</sub>	modified Froude number, $\bar{V}_j^2 / a d$
H	distance between nozzle tip and liquid surface, cm
H/d	dimensionless nozzle height
h	penetration depth into liquid measured along axis of symmetry, cm
K <sub>1</sub> , K <sub>2</sub>	empirical constants
L	nozzle length, cm
M	jet momentum flux, N

R	radius of curvature at stagnation point, cm
Re	Reynolds number, $\bar{V}_J d / \nu_g$
V	velocity, cm/sec
$\bar{V}$	average velocity, cm/sec
We <sub>M</sub>	modified Weber number, $\rho_g \bar{V}_J^2 d / \sigma$
$\mu$	viscosity, cP
$\nu$	kinematic viscosity, $\mu / \rho$ , cm <sup>2</sup> /sec
$\rho$	density, g/cm <sup>3</sup>
$\sigma$	surface tension of liquid, N/cm (dynes/cm)

Subscripts:

c	characteristic
g	gas
J	jet
$\ell$	liquid
max	maximum
par	parabolic profile

## ANALYSIS

### Gas Impingement Model

The assumed mathematical model for gas-jet impingement is an axisymmetric gas cavity located directly below a circular nozzle. A schematic drawing showing the parameters of the model is presented in figure 1. In the model, an incompressible, inviscid laminar gaseous jet with an initially parabolic velocity profile interacts with a liquid surface of infinite extent. The jet penetrates the liquid surface at right angles and forms a smooth gas cavity under steady-state conditions. An axisymmetric coordinate system is chosen with an origin located at the point 0 (as shown in fig. 1). The liquid has surface tension  $\sigma$  and density  $\rho_\ell$  and is initially located at a distance  $H$  from the nozzle and at right angles to it. Because the liquid surface is assumed to be of infinite extent, the gas penetration that results in a cavity will not appreciably affect the distance  $H$ . While the distance  $H$  will not affect a solution using an inviscid model, in experimental applications it should be kept as small as possible to minimize jet spreading. In reference 2,

a value of 3 nozzle diameters was chosen for  $H$ . As was shown in reference 10, this value is acceptable since the centerline velocity and velocity profile are altered only slightly.

The gas has density  $\rho_g$  and is traveling with some velocity  $V_{J,c}$ . The lowest point on the liquid-gas interface is the position at which the jet velocity is zero and is defined as the stagnation point. The penetration depth into the liquid surface measured along the axis of symmetry and locating the stagnation point is defined as  $h$ . By means of this model, equations are developed to predict the penetration depth into the liquid surface as a function of both liquid and gas parameters for small values of  $H$ , and they include both gravitational and surface-tension effects.

For a circular nozzle of diameter  $d$ , Boussinesq's formula shows that the exiting velocity profile will be a function of the nozzle length and the Reynolds number. Initially, the velocity profile entering the nozzle will be irregularly shaped, but as the length of the nozzle increases, the profile approaches a fully developed parabolic shape commonly known as Hagen-Poiseuille flow. Parabolic profiles prevail if the following condition is met:

$$\frac{L}{d} \geq 0.0145 \text{ Re} \quad (1)$$

where

$$\text{Re} = \frac{\bar{V}_J d}{\nu_g}$$

From reference 11, for the case of a fully established parabolic flow, the maximum jet velocity along the centerline  $V_{J,\max}$  is twice the average jet velocity  $\bar{V}_J$ , as determined by mass conservation laws. The total momentum flux for a gaseous jet possessing a completely parabolic profile is

$$M_{\text{par}} = \frac{4}{3} \rho_g A \bar{V}_J^2 \quad (2)$$

where  $A$  is the cross-sectional area of the circular nozzle.

## Governing Equations

The impingement of a parabolic gas jet on a liquid surface under weightless conditions was studied in reference 2. For small distances from the nozzle (i. e. ,  $H/d \leq 3$ ),

where jet spreading is insignificant, the following correlation was obtained for the penetration depth:

$$h = 1.75 \left( \frac{\rho_g}{\sigma} \right) \left( \bar{V}_J d \right)^2 \quad (3)$$

Further, if under weightless conditions Bernoulli's equation is applied along a streamline between the stagnation point and some point along the jet centerline in the region of the liquid-gas interface, the following equation is derived:

$$\frac{1}{2} \rho_g V_J^2 = \frac{2\sigma}{R} \quad (4)$$

where  $V_J$  is the jet velocity along the centerline in the region of the liquid-gas interface, and  $R$  is the radius of curvature at the stagnation point. If the experimental correlation (eq. (3)) and Bernoulli's equation (4) are equated, the radius of curvature at the stagnation point  $R$  can be found for  $H/d \leq 3$ . This calculation yielded the following value for  $R$ :

$$R = 1.75 \frac{d^2}{h} \quad (5)$$

## Gravitational Effects

The effect of gravity on the penetration depth can be taken into account by simply adding the gravitational pressure head to Bernoulli's equation to obtain

$$\frac{1}{2} \rho_g V_J^2 = \frac{2\sigma}{R} + \rho_\ell a h \quad (6)$$

where  $a$  is the acceleration due to gravity. Substitution of the radius of curvature from equation (5) and a subsequent rearrangement of terms yield the following expression for predicting the penetration depth when  $H/d \leq 3$ :

$$\frac{We_M}{\frac{h}{d}} = 0.57 + 0.5 Bo_M \quad (7)$$

where  $We_M$  is the modified Weber number  $\rho_g \bar{V}_J^2 d / \sigma$ , and  $Bo_M$  is the modified Bond number  $\rho_l a d^2 / \sigma$ . As can be seen, in an environment where the modified Bond number is zero (weightlessness), equation (7) reduces to the previous correlation (eq. (3)). Equation (7) yields the effects of both gravity and surface tension on the penetration depth. Data from the experimental tests will be compared with the theory. Finally, for large nozzle to liquid-surface distances (large  $H/d$ ), the important nondimensional parameters have been obtained. The constants will, of course, be different, but the important dimensionless parameters will be the modified Weber number  $We_M$ , the modified Bond number  $Bo_M$ , the dimensionless nozzle height  $H/d$ , and the dimensionless penetration depth  $h/d$ .

## APPARATUS AND PROCEDURE

Experimental testing was conducted both in normal gravity and in weightlessness. A detailed description of the 2.2-Second Zero-Gravity Facility and the experimental apparatus and procedure used for the tests conducted in weightlessness is given in reference 2. For the normal-gravity testing, the same apparatus was employed. The experimental investigation utilized a flat-bottomed, 19-centimeter-diameter, cylindrical container filled with the test liquid. Circular brass nozzles with inside diameters of 0.127, 0.191, 0.254, and 0.318 centimeter were located above the liquid surface and oriented normally to it. Data were obtained for nozzle tip to liquid surface distances ranging from 3 to 15 nozzle diameters. Nitrogen was used as the test gas that passed through the brass nozzle and subsequently impinged on the liquid surface. A 16-millimeter high-speed motion picture camera was used to record the motion of the liquid-gas interface during impingement. A list of the test parameters and the measured data are presented in table I.

The liquids employed in this study were anhydrous ethanol, trichlorotrifluoroethane, and distilled water. The properties of these liquids at 20° C can be found in table I. Similarly, the physical properties of nitrogen gas at 20° C were used.

## RESULTS AND DISCUSSION

### Description of Gas-Jet Impingement Phenomena

It has been established in reference 2 that a stable gas cavity results when a jet impinges on a liquid surface during weightlessness where the sole restoring force is surface tension. References 1 and 3 to 8 discuss the case where the sole restoring force for the existence of a stable gas cavity was gravity. It is apparent that under some combinations of the pertinent properties of the gas jet and the liquid that both gravity and surface



tension can contribute equally in the establishment of a stable gas cavity. In fact, under normal-gravity conditions, surface-tension forces may be extremely significant in determining the characteristics of the gas cavity, as indicated in the ANALYSIS section of this report.

The stable behavior of the gas cavity was observed to be similar under all conditions (i. e. , zero gravity and normal gravity). The gas cavity oscillates both vertically and laterally. These oscillations tend to become more pronounced as the incoming-gas-jet velocity increases until small bubbles of gas break away from the gas cavity and become entrained within the bulk liquid. This is defined as the onset of instability. In normal gravity, these entrained bubbles return to the gas cavity or to the liquid-gas interface because of buoyancy forces. However, in weightlessness, as observed in reference 10, the gas bubbles do not rejoin the gas but are propelled in a direction away from the liquid-gas interface. This phenomenon is termed Rayleigh instability and is discussed in detail in reference 12. Therefore, while the stable behavior during these two extremes in gravity level is similar, the unstable behavior is not. In fact, another unstable situation also indicative of the instability differences is that of spraying. Spraying has been denoted by many other terms, including sputtering, splashing, and globule stripping. Basically, spraying simply means that some mass of liquid is separated from the bulk. This type of behavior is the result of the Kelvin-Helmholtz instability (ref. 13). Spraying has been observed experimentally by Banks and Chandrasekhara in normal gravity (ref. 7). In contrast, spraying has not been observed during gas impingement normal to a liquid surface in weightlessness, and this behavior demonstrates again the radical difference in the instabilities which can occur as a function of gravity. At this time, no one has been able to correlate this phenomena since the effect of surface-tension forces in retarding the advent of Kelvin-Helmholtz instability is not completely understood. It is hoped that the role of surface tension in determining the stable cavity behavior as presented in this report will yield some insight into this complex fluid behavior.

## Comparison of Experiment With Theory

A comparison between the theory, equation (7), and the experimental data is shown in figure 2 for a dimensionless nozzle height of 3. A line was faired through the experimental data, and the equation representing this line is

$$\frac{We_M}{\frac{h}{d}} = 0.57 + 0.9 Bo_M \quad (8)$$

The experimental curve fit has a greater slope than the theoretical line, and the difference indicates that the nondimensional penetration depths ( $h/d$ ) were generally not as large as expected. The difference between theory and experiment may be due to the employment of an inviscid analysis of the gas-jet - liquid interaction. More significant than the observed discrepancy between experiment and theory is the fact that the important nondimensional parameters have been established. For any particular nondimensional nozzle height, they are the modified Bond and Weber numbers and the dimensionless penetration depth. It is noted that all tests except for the zero modified Bond number were conducted in normal gravity using small-diameter nozzles (as low as 0.127 cm). The zero modified Bond number data in figure 2 were the result of a previous study by the first author (ref. 2) and represent the arithmetic average of the parameter  $We_M/(h/d)$ .

### Zero-Gravity Penetration Depth

It is of interest to extend the correlation obtained in figure 2 for a nondimensional nozzle height of 3 to larger heights since in reality they may have more practical applicability. The proposed expression for correlating the gas impingement data is written as

$$\frac{We_M}{\frac{h}{d}} = K_1 \left( \frac{H}{d} \right) + K_2 \left( \frac{H}{d} \right) Bo_M \quad (9)$$

where  $K_1$  and  $K_2$  are empirical constants which are functions of the nondimensional nozzle height only. A series of experimental tests was conducted in weightlessness ( $Bo_M = 0$ ) at dimensionless nozzle heights of 5, 7, 10, and 15. The left side of equation (9) was evaluated, and the results of this experimental investigation are shown graphically in figure 3. A value of  $We_M/(h/d)$  was determined by an arithmetic average for each dimensionless nozzle height, and a line was faired through these averages. The line represents  $K_1(H/d)$ , the zero-gravity constant in the correlating equation (eq. (9)). As the figure shows, the constant  $K_1$  increases rapidly up to about 6 or 7 diameters away from the liquid surface and then levels off considerably. It is noted that, at 7 nozzle diameters,  $K_1$  reads 90 percent of its final value. An increase in  $K_1$  indicates that, for a constant modified Weber number, the nondimensional penetration depth decreases with increasing dimensionless nozzle height. Physically, the variation in  $K_1$  is indicative of the effect of surface tension on the stable cavity behavior.

## Effects of Nozzle Height and Modified Bond Number on Penetration Depth

Data were obtained in normal gravity at dimensionless nozzle heights of 5, 7, 10, and 15 and were plotted in figure 4 according to the proposed correlating equation

$$\frac{We_M}{\frac{h}{d}} = K_1 \left( \frac{H}{d} \right) + K_2 \left( \frac{H}{d} \right) Bo_M$$

The initial point of these curves (modified Bond number of zero) is the value of  $K_1(H/d)$ , as obtained from figure 3. Representative lines were faired through the data for each nozzle height. The equation for each line was calculated and is shown on each graph. The constants  $K_2(H/d)$  for each nozzle height of figure 4 (the slope of the lines) were plotted as a function of nozzle height in figure 5. As shown, there was almost no change in  $K_2$  up to about 7 diameters above the liquid surface, after which  $K_2$  increased rapidly. The values of  $K_2(H/d)$  physically represent the contribution of gravitational forces in determining the stable penetration depth during gas-jet impingement.

The results of the previous sections indicate that the general correlating equation given in equation (9) may be expressed as follows:

$$\frac{We_M}{\frac{h}{d}} = K_1 + K_2 Bo_M$$

where the zero-gravity constant  $K_1$  (fig. 3) and  $K_2$  (fig. 5) are functions of  $H/d$ .

### Limiting Case - High Modified Bond Number

Let us now examine the limiting case of high modified Bond number, those cases where surface-tension forces become negligible. In this situation, the second term of the right side of equation (9) becomes more dominant than the first term and leads to the expression

$$\frac{We_M}{\frac{h}{d}} = K_2 Bo_M \tag{10}$$

This last equation is proposed to be applicable for gravity-dominated cases. Rewriting equation (10) in terms of the variables results in the following equation:

$$\frac{h}{d} = \frac{1}{K_2} \frac{\rho_g}{\rho_l} \frac{\bar{V}_J^2}{ad} \quad (11)$$

It is now possible to compare equation (11) with the results of other investigators of normal-gravity penetration depths. Reference 1 was chosen to be representative for this purpose. After some simplification, the results of reference 1 can be expressed as

$$\frac{h}{d} = f\left(\frac{H}{d}\right) \frac{\rho_g}{\rho_l} \frac{\bar{V}_J^2}{ad} \quad (12)$$

The quantity  $f(H/d)$  follows the same trend as  $K_2^{-1}$ , that is, it decreases with increasing  $H/d$ . The absolute magnitudes of these functions disagree considerably at small values of  $H/d$  and approach each other and agree quite well for higher values of  $H/d$ . The difference in these values is to be expected since reference 1 investigated turbulent jets possessing initially flat velocity profiles.

In conclusion, equation (11) is therefore valid for laminar jets possessing initially parabolic velocity profiles in regions where surface-tension forces are negligible. The quantity  $\bar{V}_J^2/ad$  is defined as the modified Froude number and allows the gravity-dominated penetration depth to be expressed as follows:

$$\frac{h}{d} = \frac{1}{K_2} \frac{\rho_g}{\rho_l} Fr_M \quad (13)$$

## SUMMARY OF RESULTS

An experimental and analytical investigation which examined gas-jet impingement on a liquid surface was conducted at the NASA Lewis Research Center. A laminar gaseous nitrogen jet exiting from a circular nozzle was used to obtain an initially parabolic velocity profile. The penetration depths resulting from the jet impinging normally on various liquid surfaces were measured. The nozzle diameters ranged in size from 0.127 to 0.318 centimeter. Both normal- and zero-gravity tests were conducted using the 2.2-Second Zero-Gravity Facility. Penetration depths were measured at 3, 5, 7, 10, and 15 nozzle diameters from the liquid surface. The following results were obtained:

1. The penetration depth into the liquid was correlated with the system parameters where the parameters involved in the correlation were obtained from an inviscid analysis:

$$\frac{We_M}{\frac{h}{d}} = K_1 + K_2 Bo_M$$

where  $We_M$  is the modified Weber number, equal to  $\rho_g \bar{V}_J^2 d / \sigma$ ,  $\rho_g$  is the gas density,  $\bar{V}_J$  is the average jet velocity,  $d$  is the nozzle diameter,  $\sigma$  is the surface tension of the liquid,  $h$  is the penetration depth into the liquid,  $K_1$  and  $K_2$  are constants,  $Bo_M$  is the modified Bond number, equal to  $\rho_\ell a d^2 / \sigma$ ,  $\rho_\ell$  is the liquid density, and  $a$  is acceleration due to gravity.

2. The functions  $K_1$  and  $K_2$  varied with the nozzle height  $H/d$ , where  $H$  is the distance between the nozzle tip and the liquid surface. In general, both  $K_1$  and  $K_2$  increase with increasing  $H/d$ .

3. The following expression was found to predict gravity-dominated penetration depths (i. e. , surface-tension forces negligible):

$$\frac{h}{d} = \frac{1}{K_2} \frac{\rho_g}{\rho_\ell} Fr_M$$

where  $Fr_M$  is the modified Froude number, equal to  $\bar{V}_J^2 / ad$ . The form of this expression is similar to that obtained by previous investigators of gravity-dominated systems.

Lewis Research Center,  
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Cleveland, Ohio, March 19, 1971,  
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TABLE I. - SUMMARY OF PARAMETERS

Liquid	Surface tension, <sup>a</sup> $\sigma$ , N/cm (dynes $\times 10^5$ /cm)	Liquid density, <sup>a</sup> $\rho_\ell$ , g/cm <sup>3</sup>	Nozzle diameter, d, cm	Average jet velocity, $\bar{V}_j$ , cm/sec	Modified Bond number, $Bo_M$	Modified Weber number, $We_M$	Dimensionless nozzle height, H/d	Average non-dimensional penetration depth, h/d	Reynolds number, Re
Distilled water	$72.75 \times 10^{-5}$	1.00	0.127	1272	0.22	3.3	3	3.8	1081
			.318	821	1.36	3.4	3	1.3	1740
			.318	821	1.36	3.4	3	1.5	1741
			.254	946	.90	3.6	3	1.9	1608
			.254	1099	.90	4.9	10	1.3	1868
			.318	1080	1.36	6.0	10	.6	2290
			.127	1482	.22	4.5	10	3.2	1260
			.318	896	1.40	4.1	5	1.7	1900
			.318	896	1.40	4.1	7	1.3	1900
			.127	2584	.22	13.7	15	4.0	2196
			.127	2325	0	11.1	15	8.4	1976
			.127	1482	0	4.5	15	2.8	1260
			.191	1470	0	6.4	10	4.3	1870
			.127	1482	0	4.5	10	3.0	1260
			.127	1686	0	5.8	10	4.8	1433
			.254	761	0	2.4	7	1.6	1294
			.191	1470	0	6.4	5	6.3	1870
			.254	761	0	2.4	5	1.7	1294
Anhydrous alcohol	$22.3 \times 10^{-5}$	0.789	0.127	1272	0.22	3.3	3	3.8	636
			.318	605	3.5	4.9	3	1.4	1283
			.254	761	2.3	7.6	3	2.4	1294
			.127	1061	.56	7.6	10	4.2	902
			.127	857	.56	4.9	5	3.6	728
			.127	857	.56	4.9	7	4.2	728
			.127	1170	.56	9.0	15	4.4	995
			.254	1690	2.3	38.1	15	1.6	2873
			.254	642	2.3	5.5	10	1.7	1091
			.254	642	2.3	5.5	7	1.9	1091
			.254	642	2.3	5.5	5	2.2	1091
			.254	642	2.3	5.5	10	1.1	1091
			.254	811	2.3	8.8	10	1.6	1379
			.127	1272	.56	10.8	15	3.3	1081
			.254	679	2.3	6.1	10	1.1	1154
Trichlorotrifluoroethane	$18.6 \times 10^{-5}$	1.579	0.191	744	3.03	6.7	3	2.3	945
			.318	702	8.40	9.9	3	1.4	1488
			.254	761	5.4	9.3	3	1.7	1294
			.191	1116	3.03	14.8	10	1.0	1417
			.254	1099	5.4	19.1	10	.7	1868
			.191	837	3.03	8.4	5	2.1	1063
			.191	851	3.03	8.4	7	2.1	1063
			.191	2160	3.03	56.0	15	1.3	2743
			.254	629	5.4	6.5	5	1.0	1069
			.254	629	5.4	6.5	7	1.0	1069
			.254	1690	5.4	45.7	15	.6	2873

<sup>a</sup>At 20° C.

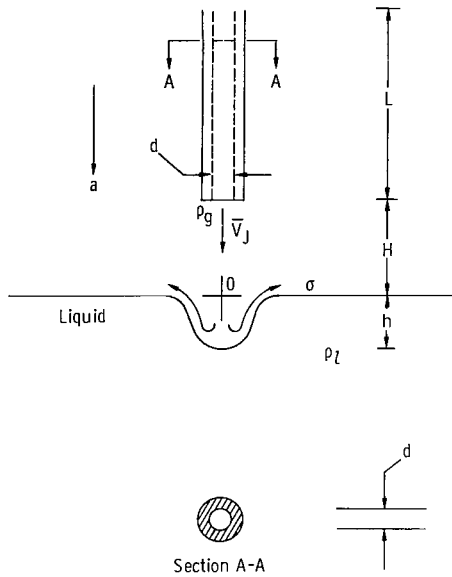


Figure 1. - Defining variables in gas impingement study.

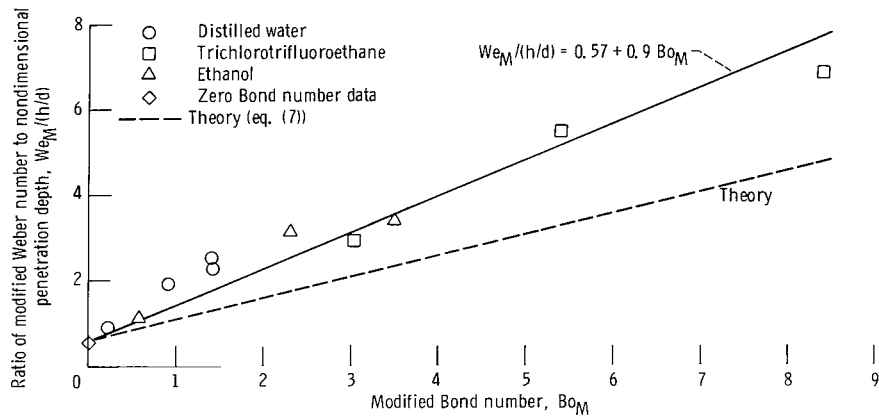


Figure 2. - Comparison of gas impingement results with theory for dimensionless nozzle height of 3.

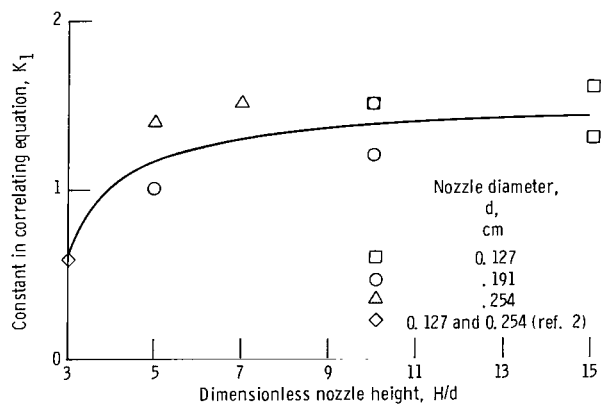


Figure 3. - Effect of nozzle height on penetration depth in zero gravity.



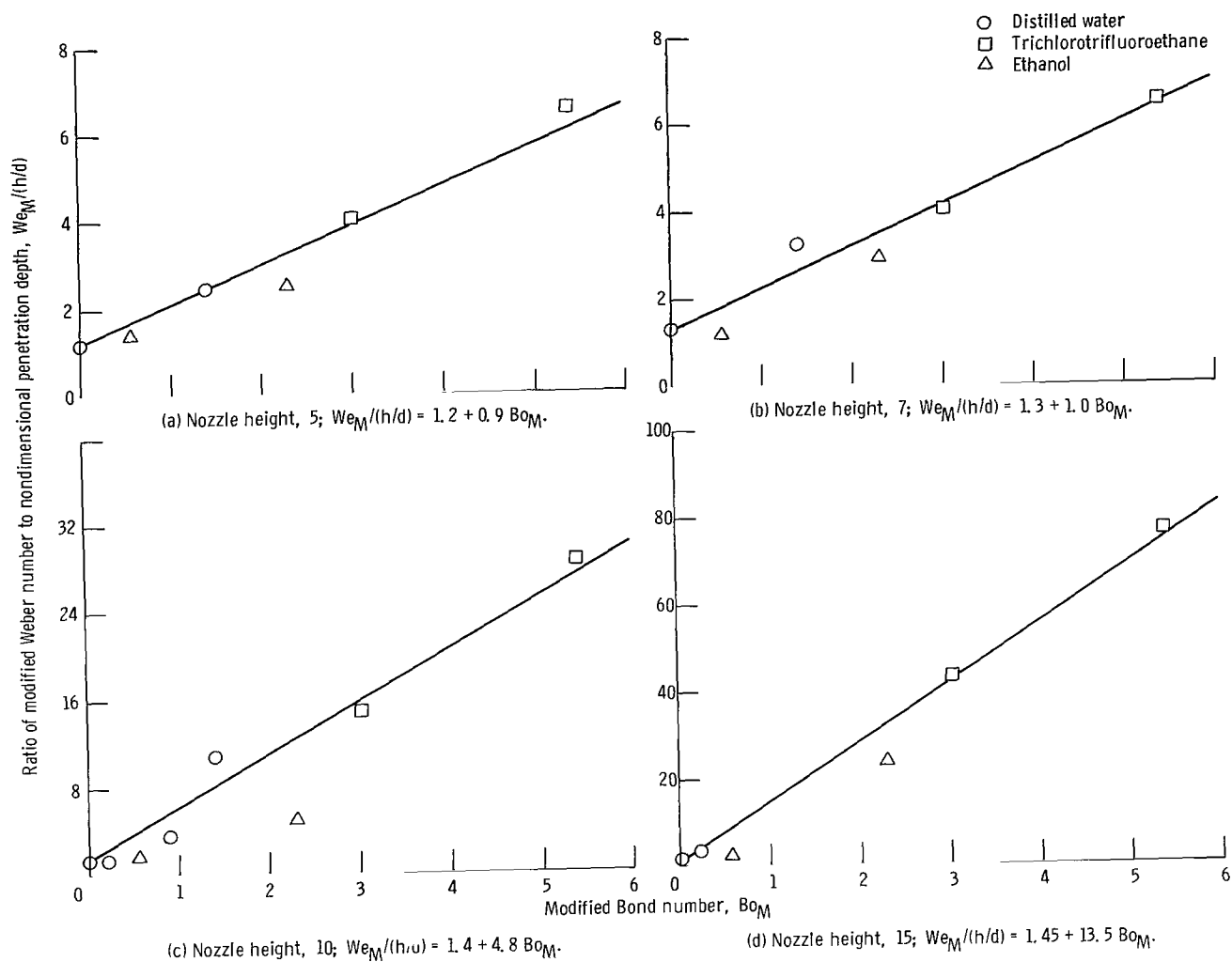


Figure 4. - Gas impingement results.

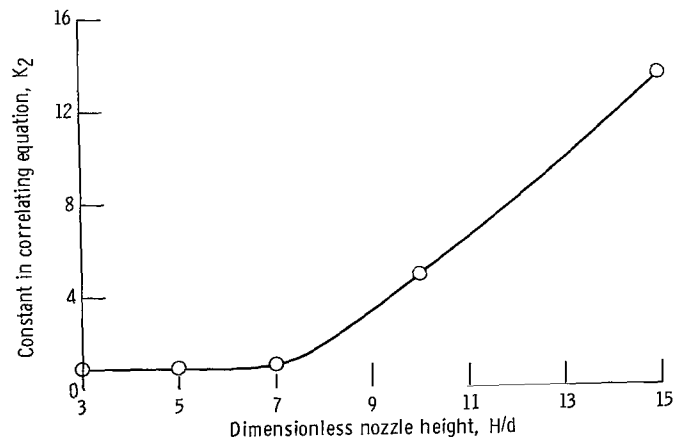


Figure 5. - Variation of constant  $K_2$  with nozzle height.

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